INTER CARRIER INTERFERENCE CANCELLATION IN OFDM SYSTEMS

Thesis submitted in partial fulfillment

of the requirements for the degree of

Master of Technology

in

Electronic Systems & Communication

by

KARNATI SHIVA KUMAR

Roll No: 211EE1324

Department of Electrical Engineering

National Institute of Technology, Rourkela

May, 2013

INTER CARRIER INTERFERENCE CANCELLATION IN OFDM SYSTEMS

Thesis submitted in partial fulfillment

of the requirements for the degree of

Master of Technology

in

Electronic Systems & Communication

by

KARNATI SHIVA KUMAR

Roll No: 211EE1324

Under the guidance of

Prof. P.K.SAHU

Department of Electrical Engineering

National Institute of Technology, Rourkela

May, 2013

National Institute of Technology

Rourkela

CERTIFICATE

This is to certify that the thesis entitled, "**INTER CARRIER INTERFERENCE CANCELLATION IN OFDM SYSTEMS**" submitted by KARNATI SHIVA KUMAR to National Institute of Technology Rourkela is a bona fide research work carried out by him under my guidance and is worthy for the award of the degree of **"Master of Technology"** in Electrical Engineering specializing in **"Electronic Systems & Communication"** from this institute. The embodiment of this thesis is not submitted in any other university and/or institute for the award of any degree or diploma to the best of our knowledge and belief.

Date:

Prof. P.K.SAHU

Dept. of Electrical Engineering

National Institute of Technology

Rourkela-769008

Acknowledgements

I am grateful to numerous local and global peers who have contributed towards shaping this thesis. At the outset, I would like to express my sincere thanks to Prof. P.K.Sahu for his advice during my thesis work. As my supervisor, he has constantly encouraged me to remain focused on achieving my goal. He has helped me greatly and been a source of knowledge. I extend my thanks to our HOD, Prof. Anup Kumar Panda for his valuable advices and encouragement.

I am really thankful to my all friends. My sincere thanks to everyone who has provided me with kind words, a welcome ear, new ideas, useful criticism, or their invaluable time, I am truly indebted.

I must acknowledge the academic resources that I have got from NIT Rourkela. I would like to thank administrative and technical staff members of the Department, who have been kind enough to advise and help in their respective roles.

Last, but not the least, I would like to dedicate this thesis to my family, for their love, patience, and understanding.

Karnati shiva kumar

Roll no: 211EE1324

Abstract

In the area of wireless communications, the demand for high data rate transmission is rapidly increasing. Orthogonal frequency division multiplexing (OFDM) is known to be a promising technique for high-rate transmission that can overcome the inter symbol interference (ISI) which results from the time dispersive nature of wireless channels. For OFDM communication systems the orthogonality is lost among the sub-carriers due to frequency offset which results in Inter carrier Interference (ICI). This ICI rapidly degrades the performance of OFDM system. We have so many ICI cancellation methods like time windowing and frequency equalization to improve the BER performance of OFDM systems. In this an efficient ICI cancellation methods termed ICI self-cancellation (SC) scheme, extended Kalman filter (EKF) method and another ICI cancellation scheme, named Total ICI Cancellation scheme are proposed. However the total ICI cancellation scheme has does not lower the transmission rate or reduce the bandwidth efficiency. It is shown that for high values of the frequency offset and for higher order modulation schemes, the EKF method perform better than the SC method. The Total ICI Cancellation scheme takes advantage of the orthogonality of the ICI matrix and offers perfect ICI cancellation and significant BER improvement at linearly growing cost. Simulation results in AWGN channel confirm the superb performance of the Total ICI Cancellation scheme in the presence of frequency offset or time variations in the channel compared with other two schemes.

Contents

List of Figures

List of Tables

List of Abbreviations and Symbols

OFDM	Orthogonal Frequency Division Multiplexing
ICI	Inter Carrier Interference
SC	Self Cancellation
EKF	Extended Kalman Filter
MSE	Mean square error
CIR	Carrier to Interference Ratio
ε	Normalized frequency offset

Chapter 1

Introduction

1.1 Introduction

As the demand for high data rate communication has been increasing rapidly, it is required to overcome the problems associated with high speed communications. As the transmission signal passes through the channel it effects by many degradations, such as noise, attenuation, multipath, interference, time variation, non-linearity‘s. for a particular channel the communication designer must decide how to efficiently utilize the available channel bandwidth in order for reliable transmission within the transmitted power constraint and receiver complexity constraint. In case of low speed communications, the degradation parameter effects are small. In single carrier communication, degradation can be reduced by signal processing techniques at the receiver.

Different methods like adaptive equalization and channel coding can be used to increase the performance. However it is difficult use these methods at high data rate because inherent delay also increases with bit rate. Therefore alternative approach is multicarrier communication. Orthogonal frequency division multiplexing (OFDM) is an example of multicarrier communication and is preferred modulation scheme in modern high data rate wireless communication systems. The basic principle of OFDM technique is to split the available spectrum into N number of sub-channel bandwidths and transmission of signal using orthogonal carriers through these sub-channels. OFDM converts the frequency selective channel to frequency flat channel so that it can completely eliminate Inter symbol interference (ISI). This is the major advantage of OFDM (which is multi carrier communication) over single carrier communication.

As we know In Parallel data transmission, an available frequency band is divided into several channels by independently modulating a number of carriers of different frequency. Since each channel occupies a relatively narrow frequency band, parallel transmission is effective in combating the effects of amplitude and delay distortion and impulsive noise. But to eliminate inter channel interference problem, it is required to avoid spectral overlap of channels, which leads to poor spectral efficiency. if spectral overlap is allowed, Higher signaling rates can be achieved and some orthogonality relationship is used to minimize the interference between adjacent channels. Some commercial data terminals use this approach. During 1960's Chang has given different conditions for spectral limited channels [2], each carrying a data rate b, may be spaced b/2 apart in frequency, results no inter channel interference which leads to design of OFDM system. Under these conditions, using available bandwidth a total signaling rate close to the Nyquist rate may be achieved through the use of a large number of channels. The spectral roll-off of each sub-channel can be within the limit, thus permitting easy filter design.

In OFDM, the multiple frequency channels (sub-carriers) are orthogonal to each other. But the major problem of OFDM is frequency offset sensitivity between the transmitted and received signals, may be due to Doppler shift of the channel, or the difference between the transmitter and receiver local oscillator frequencies. This carrier frequency offset causes loss of orthogonality among sub-carriers and then signals carried by sub-carriers becomes dependent on each other, which leads to inter-carrier interference. Researchers have proposed various techniques to combat the ICI in OFDM systems [11].

In this project, the effects of ICI have been analyzed and three solutions to combat ICI have been discussed. The first method is a self-cancellation scheme, the other two techniques are extended Kalman filter (EKF) and Total ICI Cancellation approach. In the self-cancellation scheme The ICI between adjacent sub-carriers is reduced at the receiver by using redundant data transmission onto adjacent sub-carriers and it is very simple method. The main idea is to modulate one data symbol onto a group of subcarriers with predefined weighting coefficients. Hence the ICI signals generated within a group can be "self-cancelled" each other. Furthermore, simulation results under different conditions are presented which shows its advantages in certain conditions.

The Kalman filter is a remarkably versatile and powerful recursive estimation algorithm. The EKF provides a trajectory of estimation for frequency offset. The error in each update decreases and the estimate becomes closer to the ideal value during iterations. The preamble preceding each OFDM frame can be utilized as a training sequence for estimation of the frequency offset imposed on the symbols. Simulation results shows how accurate EKF can estimate frequency offset in different conditions.

Most of the existing ICI cancellation methods achieve the ICI reduction and BER performance improvement at the cost of lowering the transmission rate and reducing the bandwidth efficiency. In order to improve spectral efficiency and ICI cancellation to a great extent, Xue Li proposed one new method called The Total ICI Cancellation. The Total ICI Cancellation scheme takes advantage of the orthogonality of the ICI matrix and offers a perfect ICI cancellation and significant BER improvement at linearly growing cost. Simulation results in AWGN channel and multipath fading channel confirm the superb performance of the proposed Total ICI Cancellation scheme in the presence of frequency offset or time variations in the channel. It provides better performance compared to other ICI cancellation methods.

In this approach first we quantize the normalized frequency offset into M discrete values, leading to M spreading code matrices as candidates. Next, by decoding the received signal using these M spreading code matrices, M decisions are made on the data symbols. Using these M data symbols to recreate the received signal with ICI and measuring the Euclidean distance of the M recreated signals with the actual received signal, the best normalized frequency offset is chosen and the best corresponding data symbols are determined. Simulation results over AWGN channel and mobile multi-path fading channel demonstrate that the proposed method eliminates the ICI with less computational complexity.

1.2 History of Wireless Communications

The history of mobile communication [12, 16] can be divided into 3 periods:

- The pioneer era
- The pre-cellular era
- The cellular era

Basic research and development in the wireless communications field took place in the pioneer era. In 1860s James Maxwell proposed the existence of electromagnetic (EM) waves and demonstration of the existence of these EM waves in 1880s by Heinrich Rudolf Hertz. The Wireless telegraphy invented and first demonstrated by Guglielmo Marconi in the 1890s took place. By using basic research in wireless telegraphy, the mobile communication started using wireless telegraphy from the 1920s and this period, which is known as the pre-cellular era. In 1921 the first land-based mobile wireless telephone system is designed and operated at frequency band of 2MHz. but the first commercial wireless mobile telephone system, which is simple analog system operated in the 150MHz frequency band in Bell Telephone Laboratories in 1946. Next, in 1969, a mobile duplex system was investigated at 450MHz frequency band. The telephone exchange of this system is modified to operate automatically. Later the design of Improved Mobile Telephone System (IMTS) took place and it was practically implemented across wide range in United States. However, because coverage area is large the system is not effective in handling many users with the available frequency band.

Later the cellular zone concept was proposed to overcome this problem by considering the radio wave propagation characteristics. The cellular zone concept is splitting the large cellular site to many number of small cell sites. By using this concept same frequency channels can be used for multiple cell sites. However, the distance between the cellular sites that use the same frequency channels should be sufficiently long to avoid co channel interference. This small cellular zone concept launched the third era called as cellular era. There were many problems and issues in this system like the incompatibility of the various systems in each country or region, which includes roaming. And as the number of users' increases, analog systems could not provide sufficient capacity and quality of speech is not good.

In order to solve these problems, digital transmission schemes are initiated into mobile wireless communication system. This system is called second generation (2G) mobile communication systems, and the analog cellular era is regarded as the first generation (1G) of mobile communication systems**.** In 1G analog cellular system we have analog voice channels and digital control channels. The analog voice channels uses Frequency Modulation (FM) and the digital control channels uses simple Frequency Shift keying (FSK) modulation. Advanced Mobile Phone System (AMPS) is an analog mobile phone system standard developed by Bell Labs, and officially introduced in the Americas in 1978. It was the primary analog mobile phone system in North America (and other locales) through the 1980s and into the 2000s.

In case of 2G digital systems both voice and control channels are digital. Global system for mobile communication (GSM) is standard set developed by the European Telecommunications Standards Institute (ETSI) to describe protocols for second generation (2G) digital cellular networks used by mobile phones. This system uses a standard 2-level Gaussian Minimum Shift Keying (GMSK). Since the demand for 2G systems increased tremendously, multiple access (multiplexing) technologies were introduced and it allows many users to share the same radio spectrum. In 2G systems, we have mainly Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), and Code Division Multiple Access (CDMA). Later 2.5G and 3G technologies were introduced in order to achieve demand for higher bit-rate communication.

1.3 OFDM

OFDM is a combination of modulation and multiplexing. Multiplexing generally refers to Independent signals, those produced by different sources. In OFDM the question of Multiplexing is applied to independent signals but these independent signals are a sub-set of the one main signal. In OFDM the signal itself is first split into independent channels, modulated by data and then re-multiplexed to create the OFDM carrier. The sub-carriers should be orthogonal to each other to improve spectral efficiency. At the receiver side it is easy to recover data in each sub-carrier as long as carriers are orthogonal to each other. As more and more carriers are added, the bandwidth approaches (N+1)/N Bits per Hz. Larger number of carriers gives better spectral efficiency. The main concept in OFDM is Orthogonality of the sub-carriers.

The Orthogonality among the carriers can be maintained if the OFDM signal is defined by using Fourier transform procedures. The OFDM system transmits a large number of narrowband carriers, which are closely spaced. Note that at the central frequency of the each sub channel there is no crosstalk from other sub channels. In an OFDM system, the input bit stream is multiplexed into N symbol streams, each with symbol period Ts, and each symbol stream is used to modulate parallel, synchronous sub-carriers. The sub-carriers are spaced by 1/NTs in frequency, thus they are orthogonal over the interval (0, Ts). A typical discrete-time baseband OFDM transceiver system is shown in Figure 1.1. First, a serial-to-parallel (S/P) converter groups the stream of input bits from the source encoder into groups of log2M bits, where M is the alphabet of size of the digital modulation scheme employed on each sub-carrier. A total of N such symbols, X_m, are created. Then, the N symbols are mapped to bins of an inverse fast Fourier transform (IFFT). These IFFT bins correspond to the orthogonal sub-carriers in the OFDM symbol.

Therefore, the OFDM symbol can be expressed as

$$x(n) = \frac{1}{N}\sum_{m=0}^{N-1} X_m \, e^{j\frac{2\pi mn}{N}} \qquad 0 \le n \le N-1 \tag{1.1}$$

here $X_m$are the baseband data on each sub-carrier The digital-to-analog (D/A) converter then creates an analog time-domain signal which is transmitted through the channel.

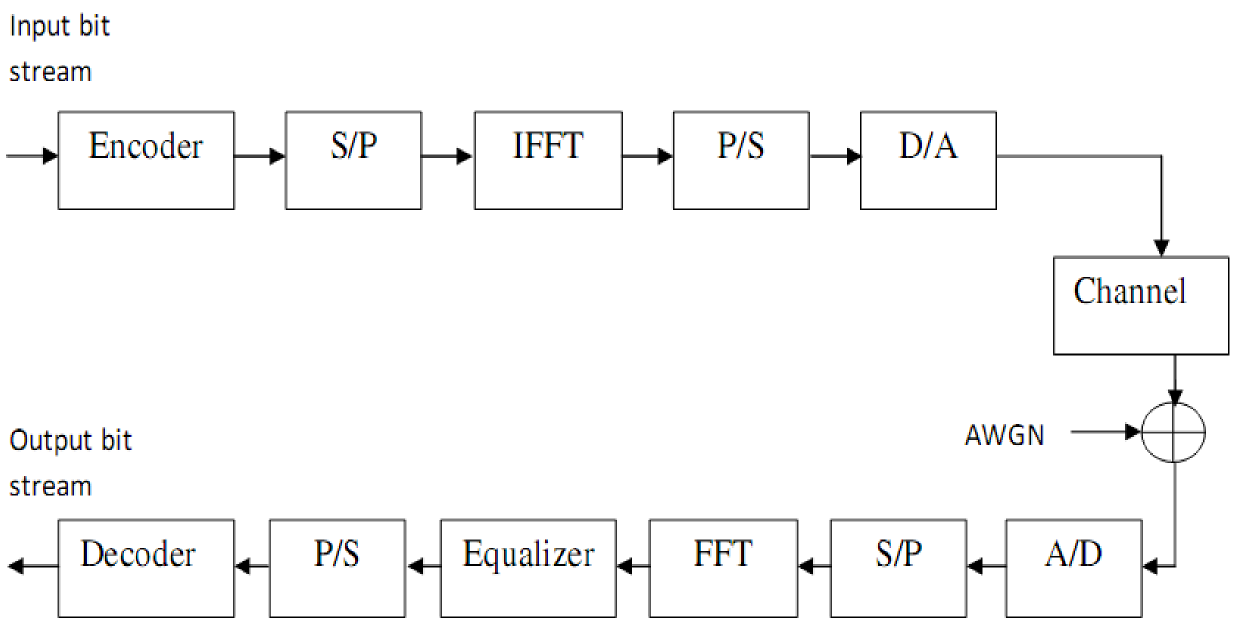


Fig 1.1: Baseband OFDM transceiver system.

At the receiver, the signal is converted back to a discrete N point sequence y(n), corresponding to each sub-carrier. This discrete signal is demodulated using an N-point fast Fourier transform (FFT) operation at the receiver.

The demodulated symbol stream is given by:

$$y(m) = \sum_{n=0}^{N-1} y(n)\, e^{-j\frac{2\pi mn}{N}} + W(m) \qquad 0 \le m \le N-1 \tag{1.2}$$

Where $W(m)$corresponds to the FFT of the samples of $W(n)$, which is the Additive White Gaussian Noise (AWGN) introduced in the channel.

1.4 Motivation

In the present communication world Multimedia is an emerging technology with widely different applications in telecommunications, computing, entertainment etc. New applications are not just in the wired environment, but also in the mobile communication. At present, only low bit-rate data services are available to the mobile users. The radio environment is random, due to the multipath and other effects. Adaptive equalization techniques at the receiver side could be the better solution in order to reduce these random effects. But as we go for higher data rate the hardware complexity increases and there are many practical problems to operate equalization methods at several Mb/sec.

Orthogonal Frequency Division Multiplexing (OFDM) is a modern technique that eliminates a need for the complex equalizers. OFDM is robust in various channel conditions and gives high spectral efficiency. It effectively reduces performance degradations due to multipath and is capable of combating deep fades in part of the spectrum. OFDM reduces Inter symbol Interference (ISI) by handling with large delay spreads, also by including the guard band in each OFDM symbol ISI can be eliminated completely. But the ICI is the main drawback of OFDM system, in this project various methods are studied to reduce ICI component.

1.5 Literature Survey

R. W. Chang: To improve spectral efficiency spectral over lapping between adjacent channels is allowed and by considering the orthogonality among parallel signals the interference between adjacent channels is minimized. In 1966 R.W. Chang proposed general conditions under which the band limited channels each carrying data of signaling rate ‘b’ may be separated by a band spacing ‘b/2’. This proposed method leads no inter channel interference among the sub-carriers and by using more no of sub-carriers, signaling rate is closer to the nyquist rate of available bandwidth can be achieved.

S. B. Weinstein: He proposed that the Fourier transform data communication system is a realization of frequency division multiplexing (FDM) in which discrete Fourier transform are computed as a part of modulation and demodulation process. Hence in OFDM the design of complex bank of modulators and demodulators can be replaced by digital fast Fourier transform (FFT) processing chips.

Peled and Ruiz: In 1980 Cyclic prefix (CP) was first introduced by Peled and Ruiz for OFDM systems. In this model cyclic extension of OFDM symbol is used instead of null guard interval and this new scheme can reduce ISI (Inter Symbol Interference) to a great extent in flat fading channels. Hence present IEEE standards are adopting this scheme.

Leonard J. Cimini: Proposed pilot-based correction, for combating the effects of multipath propagation and co-channel interference on narrow band digital mobile channel. With this proposed scheme, flat Rayleigh fading can be reduced significantly. Using this scheme signal to noise ratio increment obtained is approximately 6 dB in a bursty Rayleigh environment. And in order to avoid co channel interference a frequency offset scheme is proposed.

1.6 Objective and Outline of Thesis

The main objective of this thesis is to investigate different methods of ICI reduction. Several methods have been presented to reduce ICI, including frequency domain equalization [8], windowing at the receiver [10], ICI self-cancellation scheme [13, 15]. In this project, I have focused on the problem of ICI reduction using self cancellation, Extended Kalman Filter and Total ICI cancellation methods. Different modulation techniques are considered for ICI reduction and compared each other with BER performance. This report is organized as follows: In Chapter 2 Analysis and reduction methods of ICI are presented. In Chapter 3 modeling and simulation results are given. Chapter 4 concludes the report and scope of future work.

CHAPTR 2

Analysis and Reduction Methods of ICI

2.1 Standard OFDM System

Figure.2.1 shows the block diagram of a typical OFDM transceiver. The transmitter section converts digital data to be transmitted, into a mapping of subcarrier amplitude and phase. It then transforms this spectral representation of the data into the time domain using an Inverse Discrete Fourier Transform (IDFT). The Inverse Fast Fourier Transform (IFFT) performs the same operations as an IDFT, except that it is much more computationally efficiency, and so is used in all practical systems. In order to transmit the OFDM signal the calculated time domain signal is then mixed up to the required frequency. The receiver performs the reverse operation of the transmitter, mixing the RF signal to baseband for processing, and then uses a Fast Fourier Transform (FFT) to analyze the signal in the frequency domain. The amplitude and phase of the subcarriers is then picked out and converted back to digital data. The IFFT and the FFT are complementary function and the most appropriate term depends on whether the signal is being received or generated. In cases where the signal is independent of this distinction then the term FFT and IFFT is used interchangeably. The binary data sent at the transmitter side is compared with the binary data received at the receiver. Bit error rate is calculated by comparing both the transmitted binary data and received binary data. Here channel is considered to be additive white Gaussian.

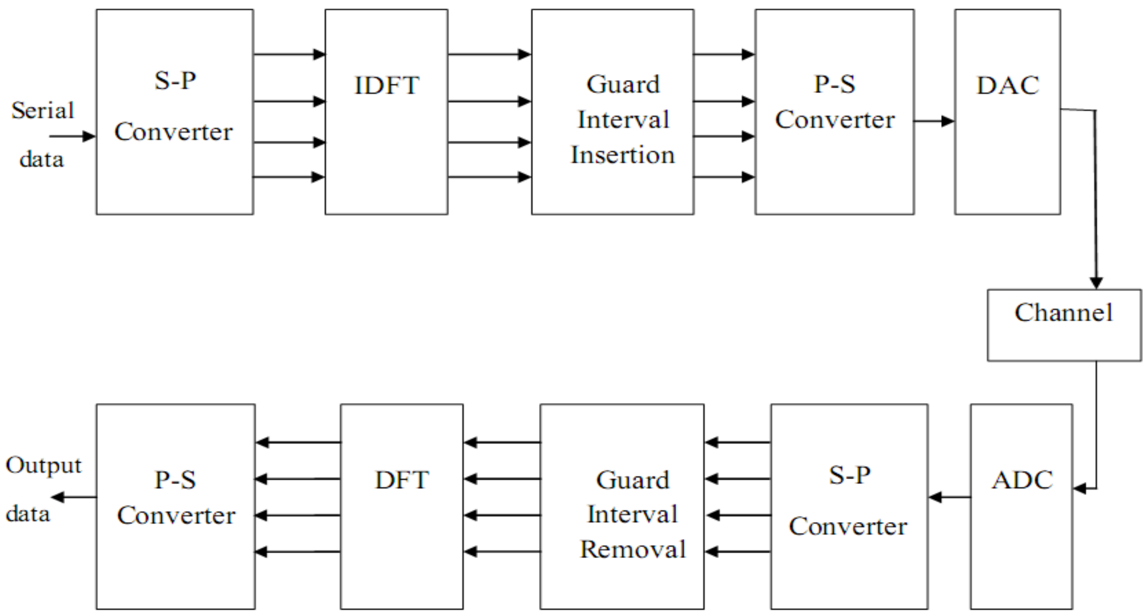


Fig 2.1: Basic block diagram of OFDM System

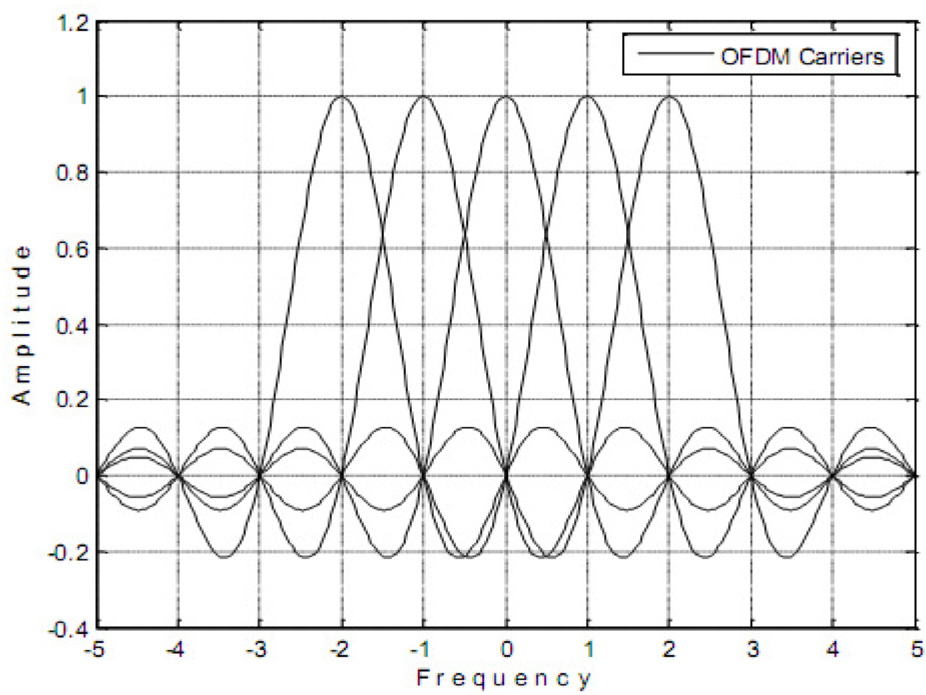


Fig 2.2: Carriers of OFDM

2.2 ICI Mechanism

From the basic mechanism of ICI The main disadvantage of OFDM, is its susceptibility to small differences in frequency at the transmitter and receiver, normally referred to as frequency offset. This frequency offset can be caused by Doppler shift due to relative motion between the transmitter and receiver, or by differences between the frequencies of the local oscillators at the transmitter and receiver. In this project, the frequency offset is modeled as a multiplicative factor introduced in the channel, as shown in below figure

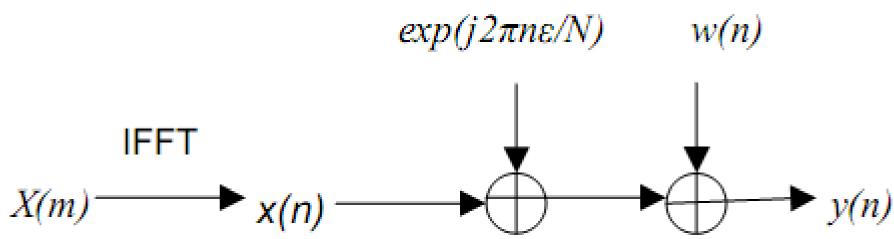


Fig 2.3: Frequency Offset Model

The received signal is given by

$$y(n) = x(n)e^{j\frac{2\pi n\varepsilon}{N}} + w(n) \tag{2.1}$$

Where ε is the normalized frequency offset, and is given by $\Delta f N T_s$. Δf is the frequency difference between the transmitted and received carrier frequencies and T_s is the subcarrier symbol period. $w(n)$ is the AWGN introduced in the channel.

The channel frequency offset normalized by the subcarrier separation is ε then received signal on subcarrier k with frequency offset effect [8] can be written as

$$Y(k) = X(k)S(0) + \sum_{l=0, l\neq k}^{N-1} X(l)S(l-k) + n_k \tag{2.2}$$

Here k =0, 1, 2… N -1

Where N is the total number of the subcarriers, $X(k)$ denotes the transmitted symbol (M ary phase-shift keying (PSK), for example) for the k^{th} subcarrier and n_k is an additive noise sample. The sequence $S(l-k)$ is defined as the ICI coefficient between l^{th} and k^{th} subcarriers [8], which can be expressed as

$$S(l-k) = \frac{\sin(\pi(l+\varepsilon-k))}{N\sin(\frac{\pi}{N}(l+\varepsilon-k))}.\exp\left(j\pi(1-\frac{1}{N})(l+\varepsilon)\right) \tag{2.3}$$

In the above equation (2.2) the first term in the right-hand side represents the desired signal. Without frequency error (ε=0), $S(0)$ takes its maximum value $S(0)=1$. The second term is the ICI component. Fig 2.4 gives ICI coefficient $S(l-k)$ when $l=0$ and $N=16$ for frequency offset values ε=0.05, ε =0.2 and ε=0.4. As ε becomes larger, the desired part $|S(0)|$ decreases and the undesired part $S(l-k)$ increases.

The carrier-to-interference ratio (CIR) is the ratio of the signal power to the power in the interference components. It has been derived from equation (2.2). In deriving the Theoretical CIR, additive noise is omitted.

The desired received signal power on the k^{th} sub carrier can be represented as

$$E\left[|C(k)^2|\right] = E\left[|X(k)S(0)|^2\right] \tag{2.4}$$

And the ICI power is

$$E\left[|I(k)|^2\right] = E\left[|\sum_{l=0,l\neq k}^{N-1} X(l)S(l-k)|^2\right] \tag{2.5}$$

Here we assumed transmitted data has zero mean and are statistically independent hence the CIR expression is

$$\text{CIR} \;=\; \frac{S(k)^2}{\sum_{l=0,l\neq k}^{N-1} S(l-k)^2} = \frac{|S(0)^2|}{\sum_{l=1}^{N-1} S(1)^2} \tag{2.6}$$

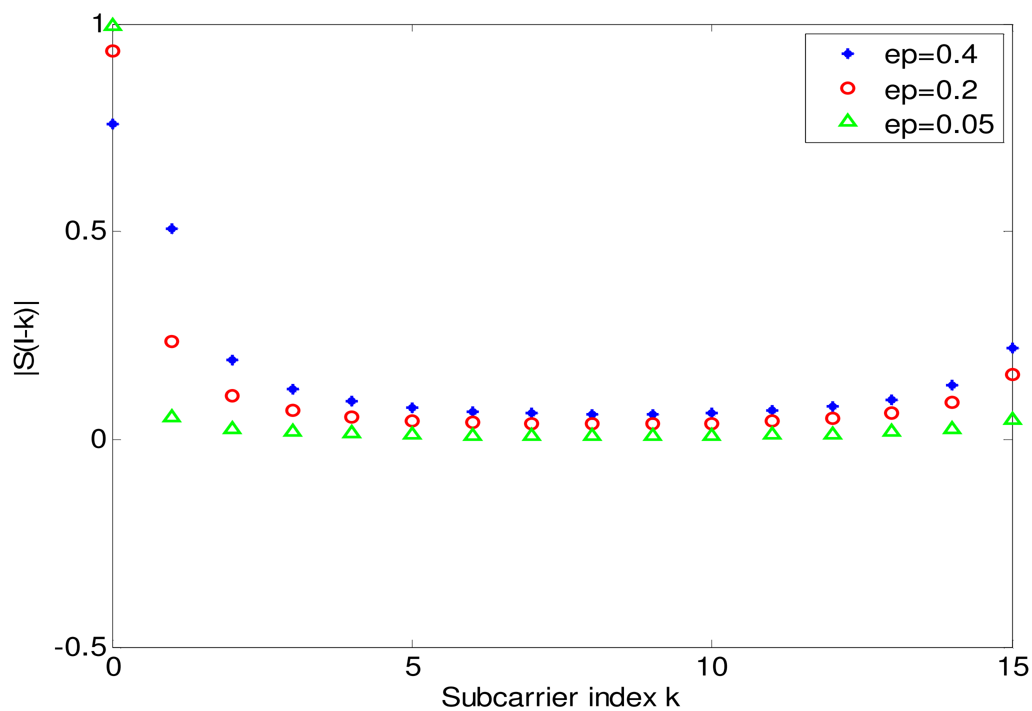


Fig 2.4: ICI Coefficients for $N=16$ carriers

Some of the methods for ICI reduction methods available in literature are:

- Frequency domain equalization
- Time domain windowing
- Pulse shaping
- ICI self cancellation
- Maximum likelihood Estimation
- Extended Kalman Filtering

From these six methods the first two methods are the initial approach, and the next two methods are very effective and the last two methods are good for higher modulation and frequency offsets.

2.3 Frequency Domain Equalization

The fading distortion in the channel causes ICI in the OFDM demodulator. The pattern of ICI varies from frame to frame for the demodulated data but remains invariant for all symbols within a demodulated data frame. Compensation for fading distortion in the time domain introduces the problem of noise enhancement. So frequency domain equalization process is approached for reduction of ICI by using suitable equalization techniques.

Drawbacks:

It can only reduce the ICI caused by fading distortion which is not the major source of ICI. The major source of ICI is due to the frequency mismatch between the transmitter and receiver, and the Doppler shift. The above method cannot address to it. Again it is only suitable for flat fading channels, but in mobile communication the channels are frequency selective fading in nature because of multipath components. Here also the channel needs to be estimated for every frame. Estimation of channel is complex, expensive & time consuming. Hence the method is not effective one.

2.4 Time Domain Windowing

We know that OFDM signal has widely spread power spectrum. So if this signal is transmitted in a band limited channel, certain portion of the signal spectrum will be cut off, which will lead to inter carrier interference. Consider the spectrum of transmitted signal as shown in fig.2.5

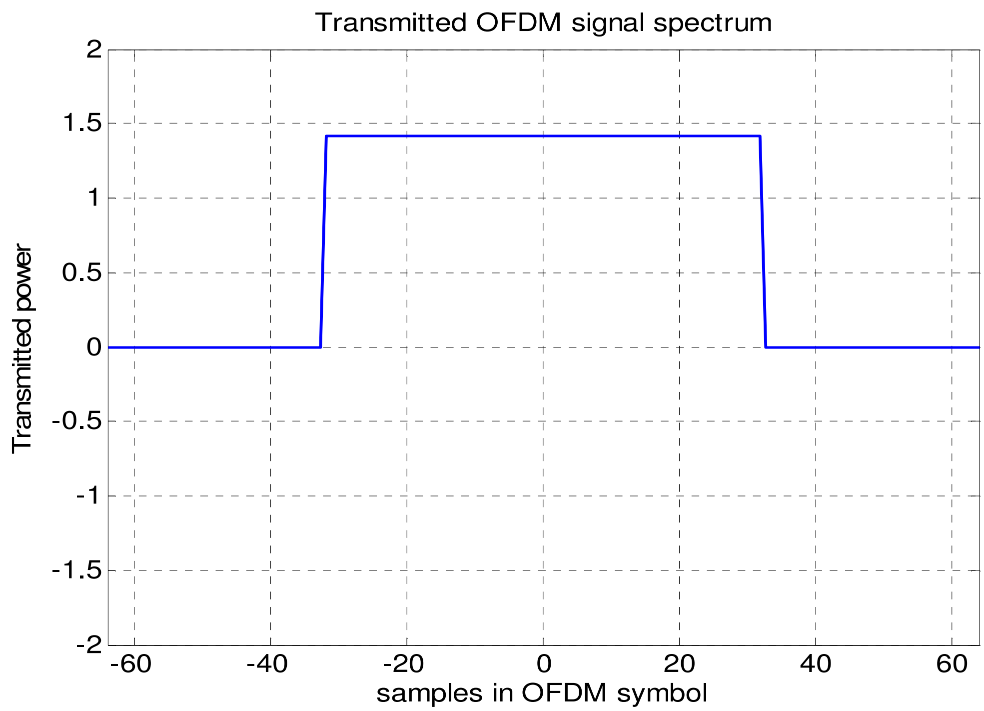


Fig 2.5: Transmitted Signal Spectrum of a 128 subcarrier OFDM

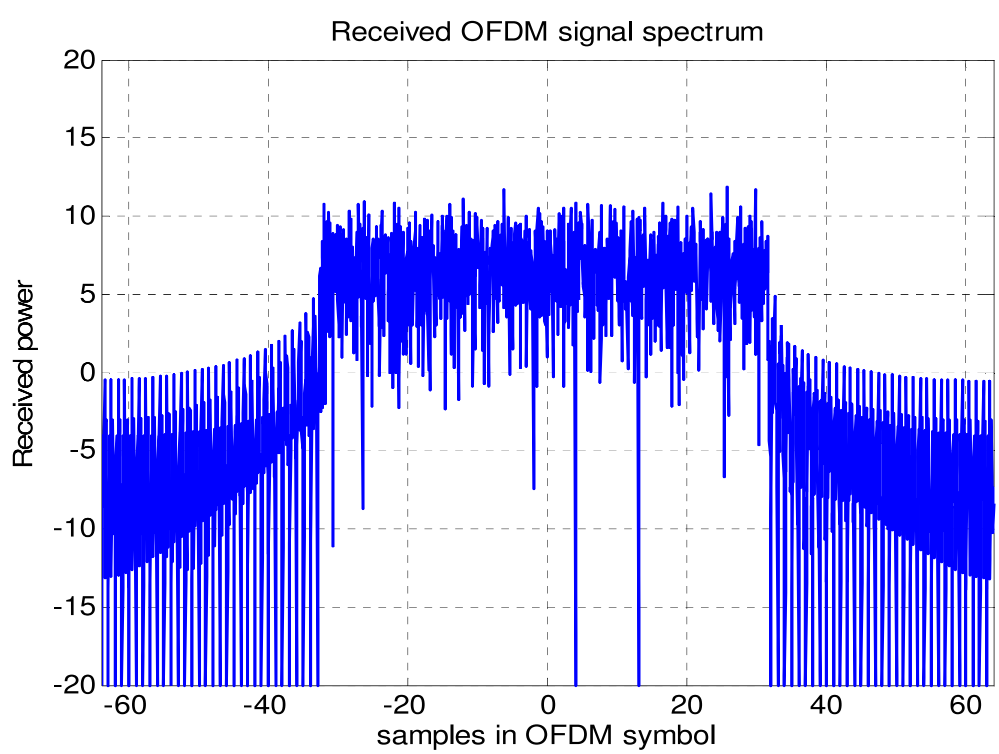


Fig 2.6: Received Signal Spectrum of a 128 subcarrier OFDM

To diminish the interference the spectrum of the signal wave form need to be more concentrated. This is achieved by windowing the signal. Basically windowing is the process of multiplying a suitable function to the transmitted signal wave form. The same window is used in the receiver side to get back the original signal. The ICI will be eliminated if the product of the window functions satisfies the Nyquist vestigial symmetry criterion.

Drawbacks:

It can only reduce the ICI caused by band limited channel which is not the major source of ICI. The major source of ICI is due to the frequency mismatch between the transmitter and receiver, and the Doppler shift. The above method cannot address to it. Windowing is done frame by frame & hence it reduces the spectral efficiency to a large extent. Hence the method is not effective one.

2.5 Pulse Shaping

We know that in OFDM system, the each carrier has one major lobe and many minor lobes with decreasing amplitude. Since at the peak point of each carrier other carrier's amplitude is zero, there is no loss of orthogonality among carriers. That is at that point the component of all other carriers is zero and hence the individual carrier is easily separated.

When there is a frequency offset the Orthogonality is lost because now the spectral null does not coincide to the peak of the individual carriers then other carriers amplitude becomes ICI to the particular carrier. The ICI power will go on increasing as the frequency offset increases. Hence the main aim of Pulse shaping is to reduce amplitude of side lobes. If we can reduce the side lobe significantly then the ICI power will also be reduced significantly. Hence a number of pulse shaping functions are proposed having an aim to reduce the side lobe as much as possible.

The significant pulse shaping functions are

(a) Rectangular pulse (REC)

(b) Raised cosine pulse (RC)

(c) Better then raised cosine pulse (BTRC)

(d) Sinc power pulse (SP)

(e) Improved Sinc power pulse (ISP)

2.6 Maximum Likelihood Estimation

Another method for frequency offset correction i.e. ML estimation in OFDM systems was suggested by Moose. In this approach, the frequency offset is first statistically estimated using a maximum likelihood algorithm and then cancelled at the receiver. This technique involves the replication of an OFDM symbol before transmission and comparison of the phases of each of the subcarriers between the successive symbols.

When an OFDM symbol of sequence length N is replicated, the receiver receives, in the absence of noise, the 2N point sequence given by

$$r(n) = \frac{1}{N}\left[\sum_{k=-K}^{K} X(k)H(k)e^{j2\pi n(k+\varepsilon)/N}\right] \tag{2.7}$$

$$k = 0,1, \ldots .N-1, \qquad N \geq 2K+1$$

Where $\{X(k)\}$ are the $2K+1$ complex modulation values used to modulate $2K+1$ subcarriers, $H(k)$ is the channel transfer function for the k^{th} carrier and ε is the normalized frequency offset of the channel.

The first set of N symbols is demodulated using an N-point FFT to yield the sequence R_1(k), and the second set is demodulated using another N-point FFT to yield the sequence R_2(k). The frequency offset is the phase difference between R_1(k) and R_2(k) is

$$R_2(\mathrm{k}) = R_1(\mathrm{k})\, e^{j2\pi\varepsilon} \tag{2.8}$$

Adding the AWGN yields

$$Y_1(k) = R_1(k) + W_1(k) \tag{2.9}$$

$$Y_2(k) = R_1(k)e^{j2\pi\varepsilon} + W_2(k) \qquad k = 0,1,\ldots.N-1 \tag{2.10}$$

The maximum likelihood estimate of the normalized frequency offset is given by

$$\hat{\varepsilon} = \frac{1}{2\pi}\tan^{-1}\left\{\frac{\left(\sum_{k=-K}^{K}\mathrm{Im}\left[Y_2(k)Y_1^*(k)\right]\right)}{\left(\sum_{k=-K}^{K}\mathrm{Re}\left[Y_2(k)Y_1^*(k)\right]\right)}\right\} \tag{2.11}$$

Once the frequency offset is known, the ICI distortion in the data symbols is reduced by multiplying the received symbols with a complex conjugate of the frequency shift and applying the FFT

$$\hat{x}(n) = FFT\left\{y(n)e^{-\frac{j2\pi n\varepsilon}{N}}\right\} \tag{2.12}$$

CHAPTER 3

Modeling & Simulation

3.1 ICI Self Cancellation Scheme

ICI self cancellation is a scheme that was introduced by Zhao and Sven-Gustav in 2001 to suppress ICI in OFDM system. The main idea is to modulate the input data symbol onto a group of subcarriers with predefined coefficients such that the generated ICI signals within that group cancel each other, hence the name self- cancellation. From Fig 2.4 we can observe that the difference between the ICI coefficient of two consecutive subcarriers are very small. This makes the basis of ICI self cancellation.

Here one data symbol is not modulated in to one sub-carrier, rather at least into two consecutive sub-carriers. If the data symbol 'a' is modulated in to the 1st subcarrier then '-a'is modulated in to the 2nd sub carrier. Hence the ICI generated between the two sub-carriers almost mutually cancels each other. This method is suitable for multipath fading channels as here no channel estimation is required. Because in multipath case channel estimation fails as the channel changes randomly. This method is also suitable for flat-channels. The method is simple, less complex & effective. The major drawback of this method is the reduction in band width efficiency as same symbol occupies two subcarriers.

3.1.1 ICI Cancelling Modulation:

From the Fig 2.4 it has been shown that the ICI coefficient gradually changed with respect to the sub-carrier index k and difference between $S(l-k)$ and $S(l+1-k)$ is very small. Therefore, if a data pair (a,-a) is modulated onto two adjacent subcarriers (l, $l+1$), where 'a' complex data, then the ICI signals generated by the subcarrier l will be cancelled out significantly by the ICI generated by subcarrier $l+1$.

Assume the transmitted symbols are constrained so that

$$X(1) = -X(0), \quad X(3) = -X(2), \ldots\ldots \; X(N-1) = -X(N-2),$$

Then from the equation (2.2), the received signal on subcarrier k becomes

$$Y'(k) = \sum_{\substack{l=0 \\ l=even}}^{N-2} X(l)[S(l-k) - S(l+1-k)] + n_k \tag{3.1}$$

And on subcarrier $k+1$ is

$$Y'(k+1) = \sum_{\substack{l=0 \\ l=even}}^{N-2} X(l)[S(l-k-1) - S(l-k)] + n_{k+1} \tag{3.2}$$

Then denote new ICI coefficient as

$$S(l-k) - S(l+1-k) = S'(l-k) \tag{3.3}$$

Clearly from above concept $|S'(l-k)| << |S(l-k)|$ and there is reduction in ICI. In addition, the summation in (3.1) only takes even values; the total number of the interference signals is reduced to half compared with that in equation (2.2). Consequently, the ICI signals in equation (3.1) are much smaller than those in equation (2.2) since both the number of ICI signals and the amplitudes of the ICI coefficients have been reduced.

3.1.2 ICI Cancelling Demodulation:

In considering a further reduction of ICI, a so called ICI cancelling demodulation scheme is analyzed. The demodulation is suggested to work in such a way that each signal at the $k+1^{\text{th}}$ subcarrier (now k denotes even number) is multiplied by "-1" and then summed with the one at the k^{th} subcarrier. Then the resultant data sequence is used for making symbol decision. It can be represented as follows

$$Y''(k) = Y'(k) - Y'(k+1) = \sum_{\substack{l=0 \\ l=even}}^{N-2} X(l)[-S(l-k-1) + 2S(l-k) - S(l+1-k)] + n_k - n_{k+1} \tag{3.4}$$

Then corresponding ICI coefficient becomes

$$S''(l-k) = -S(l-k-1) + 2S(l-k) - S(l+1-k) \tag{3.5}$$

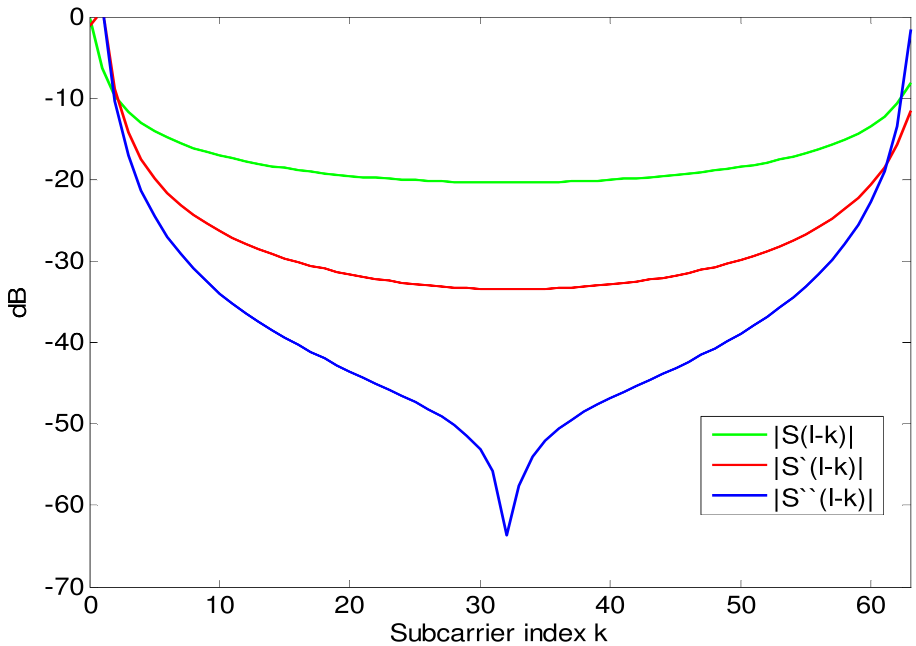


Fig 3.1: Comparison among $|S(l-k)|, |S'(l-k)|, |S''(l-k)|$ for N=64, ε=0.4

From Fig 3.1 Thus, the ICI signals become smaller when applying ICI cancelling modulation. On the other hand, the ICI cancelling demodulation can further reduce the residual ICI in the received signals. This combined ICI cancelling modulation and demodulation method is called the ICI self-cancellation scheme. Until now, three types of ICI coefficients are obtained: 1) $S(l-k)$ for standard OFDM signal. 2) $S'(l-k)$ For ICI cancellation modulation. 3) $S''(l-k)$ For combined ICI cancelling modulation and demodulation.

Using ICI coefficient given by equation (3.5), the theoretical CIR of the ICI self cancellation scheme can be given as

$$\mathrm{CIR} = \frac{|-S(-1)+2S(0)-S(1)|^2}{\sum_{l=2,4,..}^{N-1} |-S(l-1)+2S(l)-S(l+1)|^2} \tag{3.6}$$

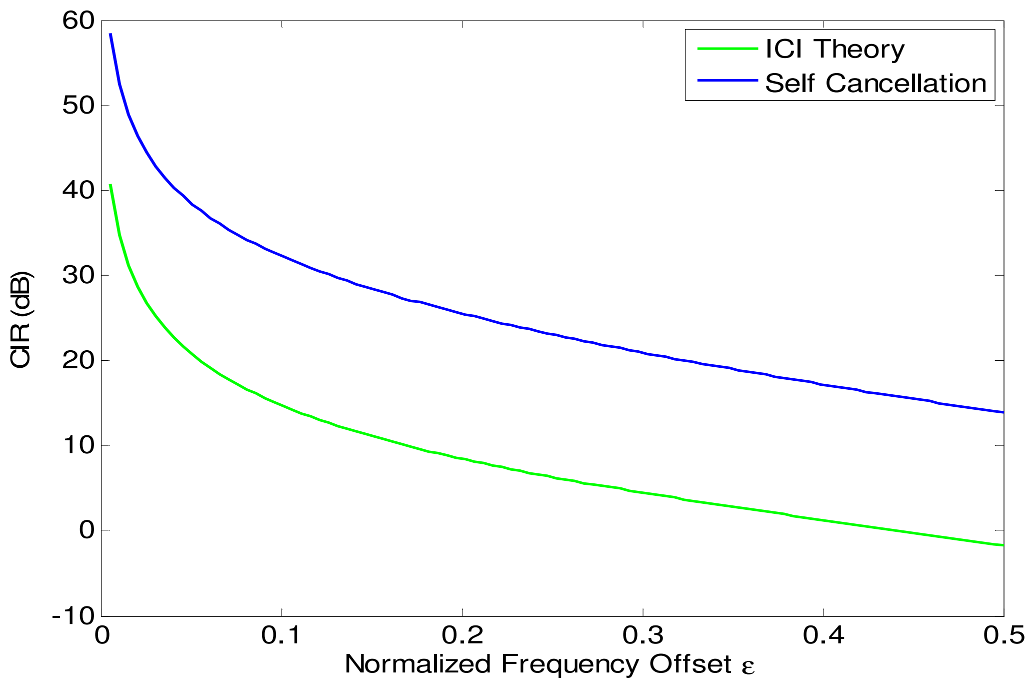


Fig 3.2: CIR versus ε for standard OFDM system

Fig.3.2 shows the theoretical CIR curve with simulation results. As a reference, the CIR of a standard OFDM system using equation (2.6) is also shown. Such an ICI cancellation scheme gives more than 15-dB CIR improvement in the range $0< \varepsilon<0.5$. Especially for small to medium frequency $0< \varepsilon <0.2$ offsets in the range, the CIR improvement can reach 17 dB. But Due to the repetition coding, the bandwidth efficiency of the ICI self-cancellation scheme is reduced by half.

3.2 Extended Kalman Filtering

Kalman filters are common in communications and signal processing literature. The Kalman filter is a remarkably versatile and powerful recursive estimation algorithm that has found various applications in communications, such as adaptive equalization of telephone channels, adaptive equalization of fading dispersive channels, and adaptive antenna arrays. As a recursive filter, it is particularly applicable to non-stationary processes such as signals transmitted in a time-variant radio channel. In estimating non-stationary processes, the Kalman filter computes estimates of its own performance as part of the recursion and use this information to update the estimate at each step. Therefore, the estimation procedure is adjusted to the time-variant statistical characteristics of the random process.

Problem Formulation:

A state-space model of the discrete Kalman filter is defined as

$$z(n) = a(n)d(n) + v(n) \tag{3.7}$$

In this model, the observation $z(n)$ has a linear relationship with the desired value $d(n)$. By using the discrete Kalman filter, $d(n)$ can be recursively estimated based on the observation of $z(n)$ and the updated estimation in each recursion is optimum in the minimum mean square sense.

As illustrated in Figure 2.3, the received symbols are

$$y(n) = x(n)e^{j\frac{2\pi n'\varepsilon(n)}{N}} + w(n) \tag{3.8}$$

It is obvious that the observation $y(n)$ is in a nonlinear relationship with the desired ε (n) value i.e.

$$y(n) = f\big(\varepsilon(\mathrm{n})\big) + w(n) \tag{3.9}$$

$$\text{Where} \quad f(\varepsilon(\mathrm{n})) = x(n)e^{j\frac{2\pi n'\varepsilon(n)}{N}} \tag{3.10}$$

In order to estimate $\varepsilon(\mathrm{n})$ efficiently in computation, we build an approximate linear relationship using the first-order Taylor's expansion:

$$y(n) = f(\hat{\varepsilon}(n-1)) + f'(\hat{\varepsilon}(n-1))[\varepsilon(\mathrm{n}) - \hat{\varepsilon}(n-1)] + w(n) \tag{3.11}$$

Where $\hat{\varepsilon}(n-1)$ is estimation of $\varepsilon(\mathrm{n}-1)$

$$f'(\hat{\varepsilon}(n-1)) = \frac{\partial f(\varepsilon(n))}{\partial \varepsilon(n)}_{\mid \varepsilon(n) = \hat{\varepsilon}(n-1} = j\frac{2\pi n'}{N}e^{j\frac{2\pi n'\varepsilon(n-1)}{N}} \tag{3.12}$$

Define

$$z(n) = y(n) - f(\hat{\varepsilon}(n-1)) \tag{3.13}$$

$$d(n) = \varepsilon(\mathrm{n}) - \hat{\varepsilon}(n-1) \tag{3.14}$$

And the following relationship:

$$z(n) = f'(\hat{\varepsilon}(n-1))d(n) + w(n) \tag{3.15}$$

Which has the same form as (3.7), i.e., $z(n)$ is linearly related to $d(n)$. Hence the normalized frequency offset $\varepsilon(\mathrm{n})$ can be estimated in a recursive procedure similar to the discrete Kalman filter. As linear approximation is involved in the derivation, the filter is called the extended Kalman filter (EKF).

The EKF provides a trajectory of estimation for $\varepsilon(\mathrm{n})$. The error in each update decreases and the estimate becomes closer to the ideal value during iterations. It is noted that the actual error in each recursion between $\varepsilon(\mathrm{n})$ and $\varepsilon'(\mathrm{n})$ does not strictly obey (3.15). Thus there is no guarantee of optimal MMSE estimates in the EKF scheme. However it has been proven that EKF is a very useful method of obtaining good estimates of the system state.

Hence this has motivated to explore the performance of EKF in ICI cancellation in an OFDM system.

3.2.1 Assumptions:

In the following estimation using the EKF, it is assumed that the channel is slowly time varying so that the time-variant channel impulse response can be approximated to be quasi-static during the transmission of one OFDM frame. Hence the frequency offset is considered to be constant during a frame. The preamble preceding each frame can thus be utilized as a training sequence for estimation of the frequency offset imposed on the symbols in this frame. Furthermore, In order to estimate frequency offset the channel is assumed to be flat-fading and ideal channel estimation is available at the receiver. Therefore in our derivation and simulation, the one-tap equalization is temporarily suppressed.

3.2.2 ICI Cancellation:

There are two stages in the EKF scheme to mitigate the ICI effect: the offset estimation scheme and the offset correction scheme.

Offset Estimation Scheme:

To estimate the quantity ε (n) using an EKF in each OFDM frame, the state equation is built as

$$\varepsilon(n) = \varepsilon(n-1) \tag{3.16}$$

i.e., in this case we are estimating an unknown constant ε. This constant is distorted by a non-stationary process $x(n)$, an observation of which is the preamble symbols preceding the data symbols in the frame. The observation equation is

$$y(n) = x(n)e^{j\frac{2\pi n'\varepsilon(n)}{N}} + w(n) \tag{3.17}$$

Where $y(n)$ denotes the received preamble symbols distorted in the channel, $w(n)$ the AWGN, and $x(n)$ the IFFT of the preambles $X(k)$ that are transmitted, which are known at the receiver. Assume there are N_p preambles preceding the data symbols in each frame are used as a training sequence and the variance σ^2 of the AWGN $w(n)$ is stationary. The computation procedure is described as follows.

1. Initialize the estimate $\hat{\varepsilon}(0)$ and corresponding state error $P(0)$.
2. Compute the $H(n)$, the derivative of $y(n)$ with respect to $\varepsilon(n)$ at $\hat{\varepsilon}(n-1)$, the estimate obtained in the previous iteration.
3. Compute the time-varying Kalman gain $K(n)$ using the error variance $P(n-1)$, $H(n)$,and σ^2
4. Compute the estimate $\dot{\hat{y}}(n-1)$, using $x(n)$and $\hat{\varepsilon}(n-1)$, i.e. based on the observations up to $n-1$,compute the error between the true observation $y(n)$and $\dot{\hat{y}}(n)$
5. Update the estimate $\hat{\varepsilon}(n)$ by adding the $K(n)$-weighted error between the observation $y(n)$and $\dot{\hat{y}}(n)$to the previous estimation$\hat{\varepsilon}(n-1)$.
6. Compute the state error $P(n)$ with the Kalman gain $K(n)$, $H(n)$, and the previous error $P(n-1)$.
7. If n is less than N_p, increment n by 1 and go to step 2; otherwise stop.

It is observed that the actual errors of the estimation $\hat{\varepsilon}(n)$ from the ideal value $\varepsilon(n)$ are computed in each step and are used for adjustment of estimation in the next step. The pseudo code of computation is summarized below.

Initialize $P(0)$, $\hat{\varepsilon}(0)$.

For $n = 1,2, \ldots . N_P$ compute

$$H(n) = \frac{\partial y(x)}{\partial x}_{|x=\hat{\varepsilon}(n)} = \frac{i2\pi n'}{N} e^{\frac{i2\pi n'\hat{\varepsilon}(n-1)}{N}} x(n)$$
$$K(n) = P(n-1)H^{*}(n)[P(n-1)+\sigma^{2}]^{-1}$$
$$\hat{\varepsilon}(n) = \hat{\varepsilon}(n-1) + \mathrm{Re}\{K(n)[y(n) - x(n)e^{\frac{i2\pi n'\hat{\varepsilon}(n-1)}{N}}]\}$$
$$P(n) = [1 - K(n)H(n)]P(n-1)$$

Through the recursive iteration procedure described above, an estimate of the frequency offset $\hat{\varepsilon}$ can be obtained.

Offset Correction Scheme:

The ICI distortion in the data symbols $x(n)$ that follow the training sequence can then be mitigated by multiplying the received data symbols $y(n)$with a complex conjugate of the estimated frequency offset and applying FFT, i.e.

$$\hat{x}(n) = FFT\{\, y(n)e^{j\frac{2\pi n'\hat{\varepsilon}(n)}{N}}\} \tag{3.18}$$

As EKF estimates the frequency offset pretty accurately, it is expected that the performance of system will be mainly influenced by the variation of the AWGN.

3.3 Total ICI Cancellation Scheme

3.3.1 ICI Orthogonality:

In standard OFDM system from equation (2.3) it has been observed that the ICI matrix in OFDM is an orthogonal matrix. Hence, from the receiver side, an OFDM with ICI can be considered as a MC-CDMA (Multi-carrier CDMA) system where all the N data symbols carried by the OFDM transmission are spread over all N subcarriers. However, since the frequency offset is time varying and unknown at the receiver side, the spreading code matrix of the equivalent MC-CDMA system is unknown. Hence, it has been proposed to transmit training sequences to estimate the frequency offset and cancel ICI via the estimated frequency offset. Hence some data rate should be allocated to training symbols for estimating the frequency offset and complexity also increases.

But In this, a new approach to solve the ICI problem in mobile OFDM system without estimating frequency offset through training symbols (and without data rate reduction) is proposed. In this approach first we quantize the normalized frequency offset into M discrete values, leading to M spreading code matrices. Next, by decoding the received signal using these M spreading code matrices, M decisions are made on the data symbols. Using these M data symbols to recreate the received signal with ICI and measuring the Euclidean distance of the M recreated signals with the actual received signal, the best normalized frequency offset is chosen and the best corresponding data symbols are determined.

Now, denote vector $\vec{X}$ as the transmitted symbol $\vec{X} = \{X(0), X(1), ...X(N-1)\}$ and vector $\vec{Y}$ as the received signal vector $\vec{Y} = \{Y(0), Y(1), ...Y(N-1)\}$, and $\vec{n} = \{n_0, n_1, ...n_{N-1}\}$

Hence we have

$$\vec{Y} = \vec{X}S + \vec{n} \tag{3.19}$$

Here S is the ICI coefficient matrix, and the p^{th} row and q^{th} column element of N X N matrix S is $S_{p,q} = S(p-q)$

The matrix S corresponds to

$$S = \begin{pmatrix} S(0) & S(-1)\cdots & S(1-N) \\ S(1) & S(0)\cdots & S(2-N) \\ \vdots & \vdots & \vdots \\ S(N-1) & S(N-2)\cdots & S(0) \end{pmatrix} \tag{3.20}$$

Now From equation (3.19), it is obvious that the received signal can be viewed as a MC-CDMA signal with N users, the k^{th} user's information symbol is $X(k)$, and the k^{th} user's spreading code is the k^{th} column of matrix S.

Now, it is important to note that the ICI coefficient matrix S is an orthogonal matrix, i.e. $SS'^{*} = I$

Here S'^{*} is the conjugate transpose of matrix S and I is identity matrix.

Hence, the OFDM signal with ICI at receiver side can be considered as an orthogonal MC-CDMA system with spreading code matrix S. As a direct result, the ICI can be totally removed from the OFDM signal if we apply a matrix multiplication to the received signal vector $\vec{Y}$:

$$\vec{R} = \vec{Y}S'^{*} = \vec{X} + \vec{n}S'^{*} \tag{3.21}$$

But, the problem is the receiver does not know the spreading code matrix S because the normalized frequency offset ε is unknown. Hence, it has been proposed to estimate the normalized frequency offset ε through some training symbols. But by doing so, some data rate needs to be allocated for the training symbols, and accurate frequency offset estimation algorithms need to be implemented at receiver side.

3.3.2 Total ICI Cancellation:

It is a new approach to eliminate ICI on mobile OFDM systems without transmitting any training symbols. While the normalized frequency offset ε is unknown to the receiver, we can quantize into M equally spaced values.

$$\varepsilon'_m = m.\Delta\,\varepsilon \quad m = 0, 1 \ldots M\ \text{-}1 \tag{3.21}$$

Where Δ ε is the quantization level of normalized frequency offset, and M is the number of quantization levels:

$$\Delta\,\varepsilon = \frac{1}{M}$$

One of these M quantized ε'_m s is closest to the true ε. Now, we are using M parallel branches at the receiver. Each branch uses one of the M quantized ε'_m s to create the corresponding ICI coefficient matrix $\tilde{S}$. Hence, we have M ICI coefficient matrices $\tilde{S}_{0,}\tilde{S}_1,\ldots\tilde{S}_{M-1}$ where m^{th} matrix corresponds to

$$\tilde{S}_m = \begin{pmatrix} S_m(0) & S_m(-1)\cdots & S_m(1-N) \\ S_m(1) & S_m(0)\cdots & S_m(2-N) \\ \vdots & \vdots & \vdots \\ S_m(N-1) & S_m(N-2)\cdots & S_m(0) \end{pmatrix} \tag{3.22}$$

Using M matrices, we can have M decisions on the transmitted data vector $\vec{X}$ where the m^{th} branch will make decision on the estimation of $\vec{X}$ as

$$\hat{\vec{X}}_m = \text{sgn}\,(\vec{Y}\tilde{S}'^{*}_m) \tag{3.23}$$

Next, with the data vector estimation $\hat{\vec{X}}_m$, each branch can reproduce the received signal $\hat{\vec{Y}}_m$ by using the data vector estimation $\hat{\vec{X}}_m$ the ICI coefficient matrix of that branch $\tilde{S}_m$

$$\hat{\vec{Y}}_m = \hat{\vec{X}}_m \ \tilde{S}_m \tag{3.24}$$

It is easy to understand that the one branch whose ε'_m is closest to the true value of ε should reproduce the received signal also closest to the received signal vector $\vec{Y}$. Hence, we only need to calculate and compare the Euclidean distances between the M reproduced received signal vectors $\hat{\vec{Y}}_m$ and the truly received signal vector $\vec{Y}$ and pick the one with the minimum distance to be the best branch and use that branch's estimated data vector as the final decision.

$$\hat{\vec{X}} = \arg\min\{\| \hat{\vec{Y}}_m - \vec{Y} \|^2\} \tag{3.25}$$

Where $\| \hat{\vec{Y}}_m - \vec{Y} \|^2$ represents the Euclidean distance between vector $\hat{\vec{Y}}_m$ and vector $\vec{Y}$

But the complexity of the proposed Total ICI Cancellation method is linearly growing with the quantization level M. The block diagram of the Total ICI Cancellation scheme is shown in Figure 3.3

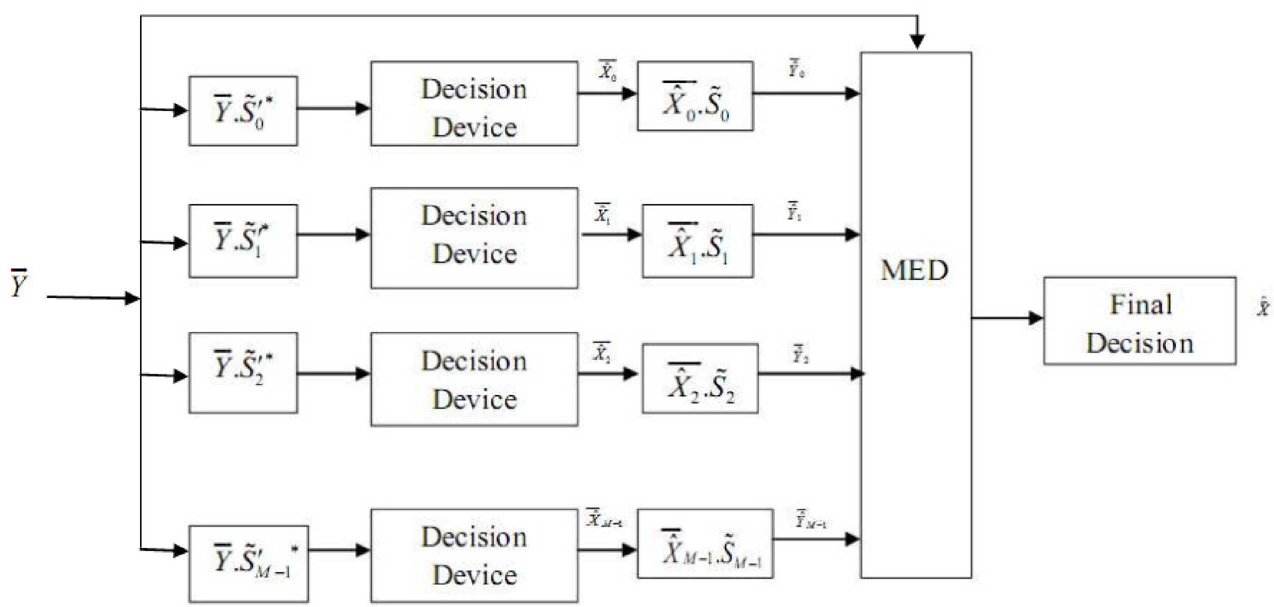


Fig 3.3: Block diagram of Total ICI Cancellation

In a multipath fading channel, we represent the complex fading gain on the k^{th} subcarrier is α_K. Then the received OFDM signal after transmission through such a fading channel with frequency offset is:

$$\vec{Y} = \vec{X}\alpha S + \vec{n} \tag{3.26}$$

Here α is a diagonal matrix α =diag $\{\alpha_0, \alpha_1, \ldots \alpha_{N-1}\}$

So the Total ICI Cancellation schemes works the same way as in AWGN channel with only one exception: the fading channel characteristics α needs to be estimated at the receiver side (which is required for OFDM transmission) and there produced received signal vector now has to consider the fading effects.

$$\hat{\hat{Y}}_m = \hat{\hat{X}}_m \, \alpha \, \tilde{S}_m \tag{3.27}$$

3.4 Simulation Results

In order to compare these three different cancellation schemes, BER curves were used to evaluate the performance of each scheme. For the simulations in this project, MATLAB was employed with its Communications Toolbox. The OFDM transceiver system was implemented as specified by Figure 2.1. Frequency offset was introduced as the phase rotation as given by (3.1). Modulation schemes of binary phase shift keying (BPSK) and 4-ary quadrature amplitude modulation (QAM) were chosen as they are used in many standards such as 802.11a. Simulations for cases of normalized frequency offsets equal to 0, 0.15, and 0.30 are given in Figure 3.1, figure 3.5 respectively without any ICI cancellation scheme.

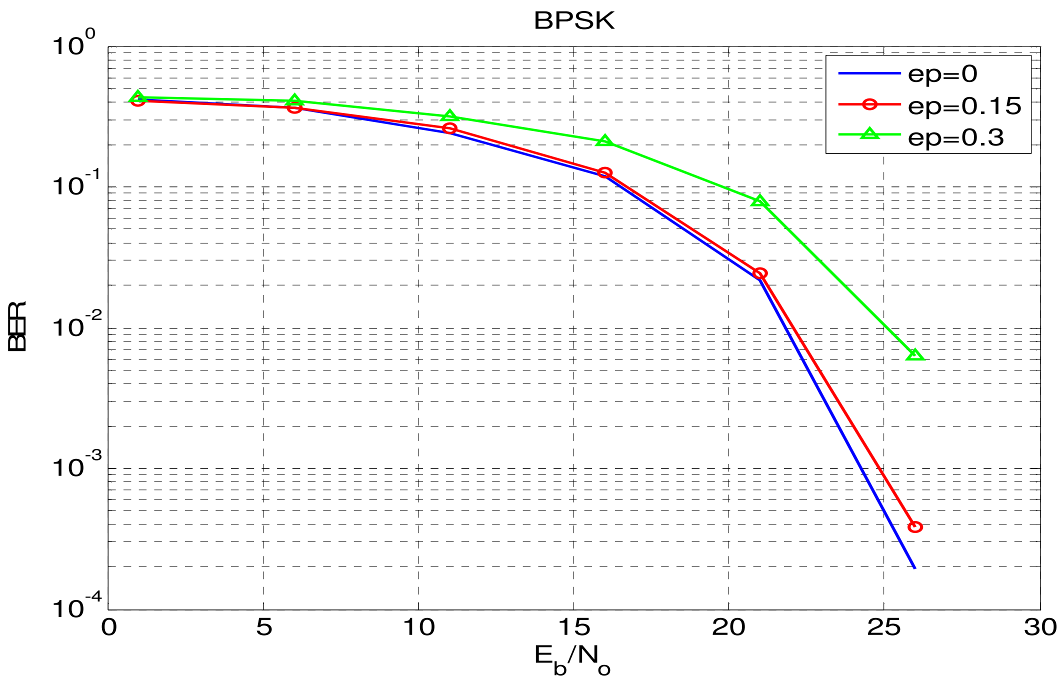


Fig 3.4: BER performance of OFDM system without ICI cancellation (BPSK)

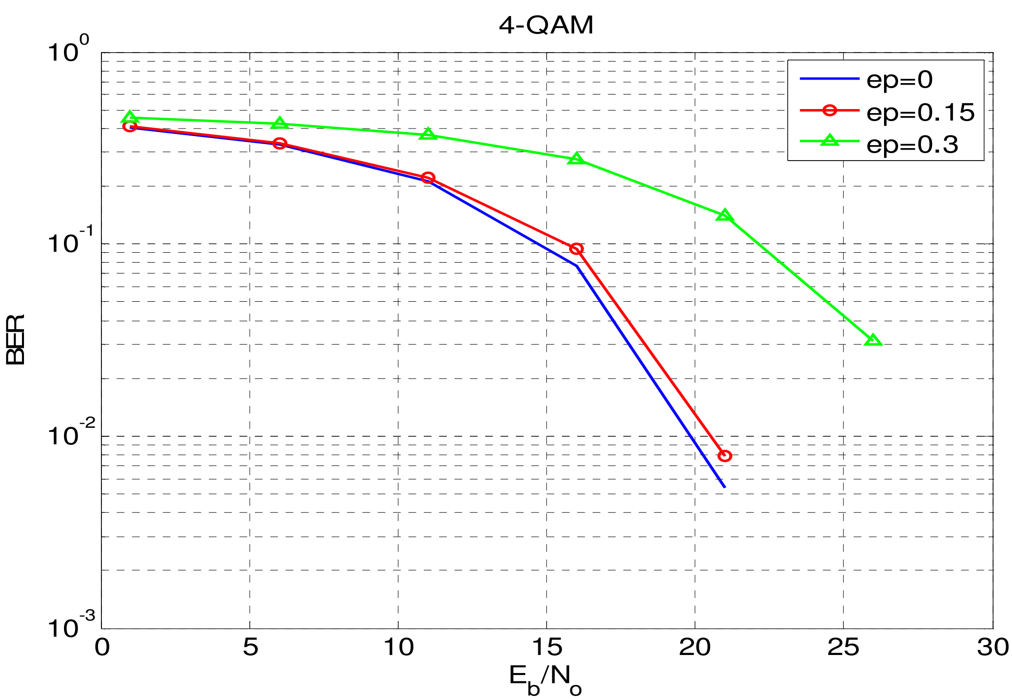


Fig 3.5: BER performance of OFDM system without ICI cancellation (4-QAM)

From above fig 3.4, fig 3.5 BER of Standard OFDM for different frequency offsets using QAM is better than of standard OFDM for different frequency offsets using BPSK. But if we go for higher modulation schemes, BER performance decreases.

Parameter	**Specifications**
FFT Size	64
Number of Carriers in OFDM symbol	52
Doppler Shift	0,0.15,0.3
Guard Length	12
Signal Constellation	BPSK,QAM
OFDM symbols for one loop	1000

Table: 3.1: Simulation conditions for Standard OFDM and ICI self cancellation methods

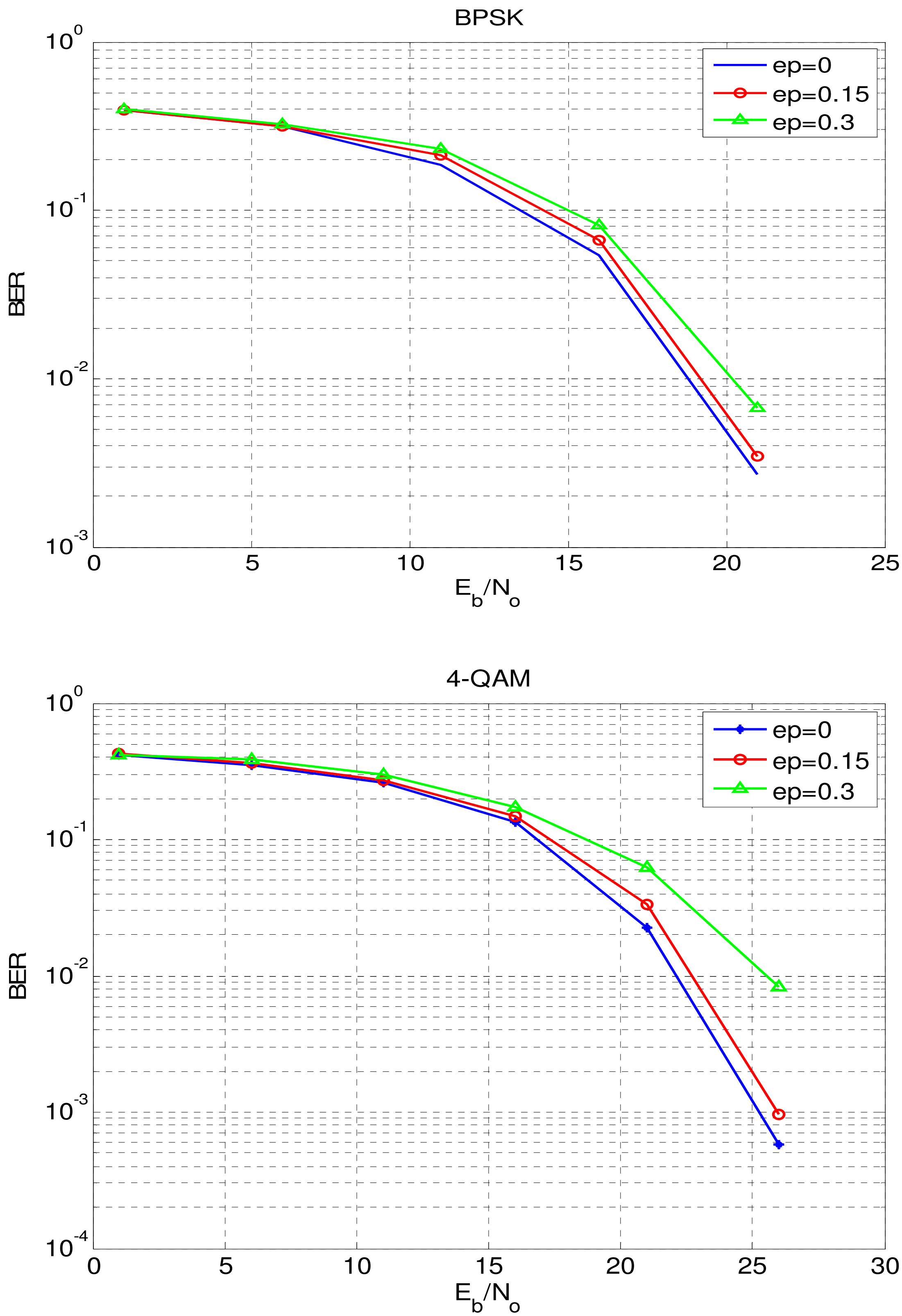


Fig 3.6: BER Performance of ICI self cancellation

Simulation results for ICI self cancellation scheme is observed in the figure 3.6. In the presence of small frequency offset and binary alphabet size, self cancellation gives the best results, i.e for BPSK, QAM-2. But in case of larger alphabet sizes and larger frequency offset such as 4-QAM and frequency offset of 0.30, self cancellation does not offer much increase in performance.

Parameter	**Specifications**
FFT Size	64
Preamble size	256
Sub-carrier size	512
Normalized frequency offset(ε)	0.05,0.15,0.3
Signal Constellation	BPSK,QAM
OFDM symbols for one loop	1000

Table 3.2: Simulation conditions for Extended Kalman filter method

Parameter	**Specifications**
FFT Size	64
Number of subcarriers(N)	52
Normalized frequency offset(ε)	0.05,0.15,0.3
Quantization levels(M)	10
Signal Constellation	BPSK,QAM
Channel	AWGN

Table 3.3: Simulation conditions for Total ICI Cancellation Scheme

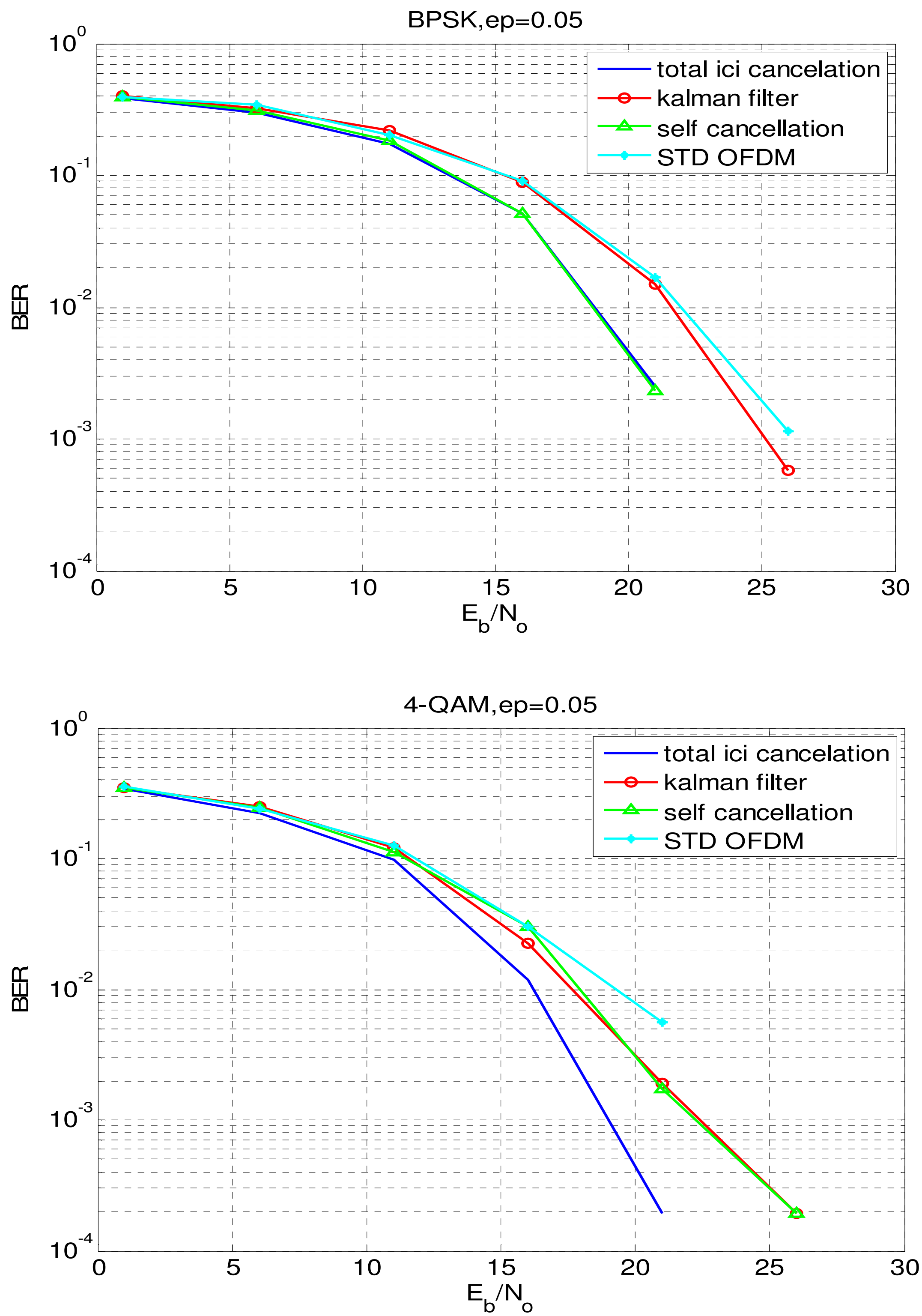
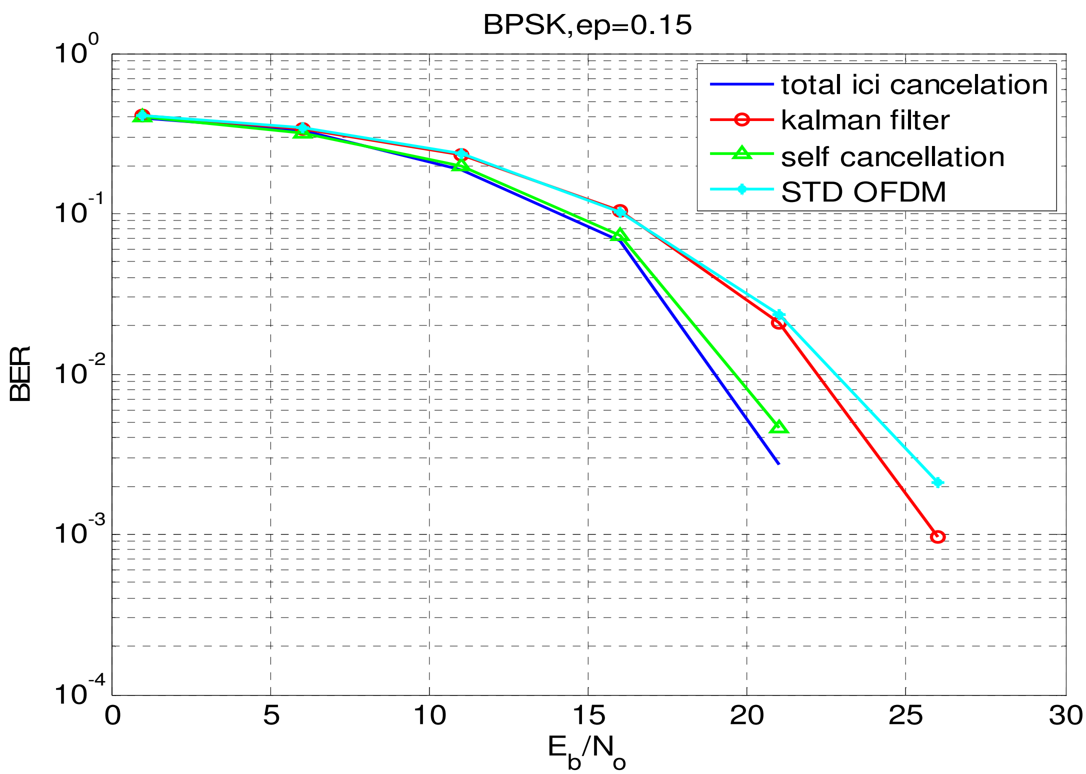


Fig 3.7: BER Performance with ε=0.05



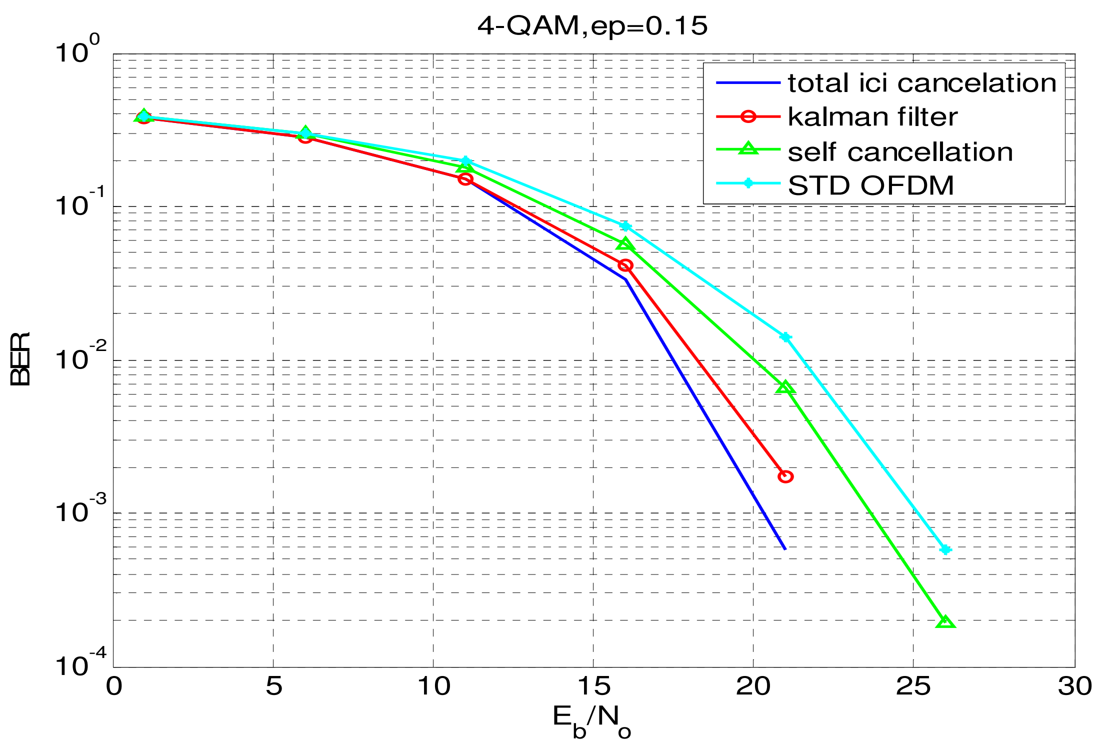
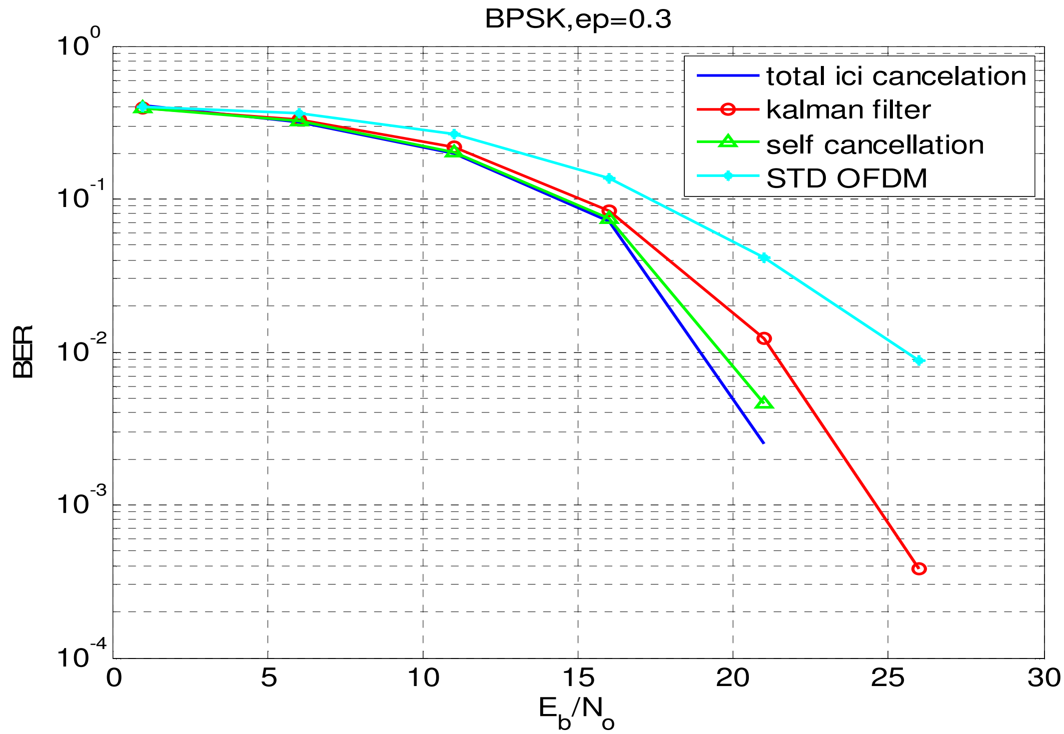


Fig 3.8: BER Performance with ε=0.15



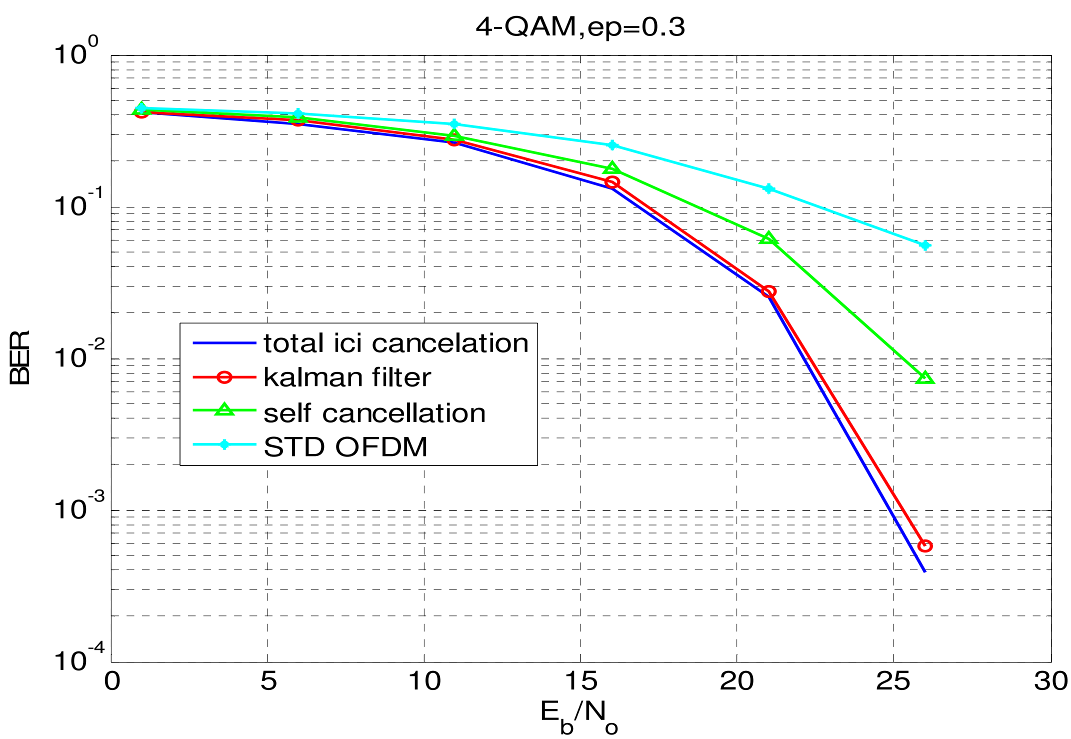


Fig 3.9: BER Performance with ε=0.30

It is observed in the figures 3.7, 3.8, 3.9 that each method has its own advantages. In the presence of small frequency offset and binary alphabet size, self cancellation gives the best results. However, for larger alphabet sizes and larger frequency offset such as 4-QAM and frequency offset of 0.30, self cancellation does not offer much increase in performance. The Total ICI cancellation scheme gives the best overall results. The Kalman filter method indicates that for very small frequency offset, it does not perform very well, as it hardly improves BER. However, for high frequency offset the Kalman filter does perform extremely well. It gives a significant boost to performance. Tables 3.4 and 3.5 summarize required values of SNR for BER specified at 10^{-2}. Significant gains in performance can be achieved using the ML and EKF methods for a large frequency offset.

Method	ε =0.05	Gain(dB)	ε =0.15	Gain(dB)	ε =0.30	Gain(dB)
STD OFDM	23		23		26	
SC	18	5	18	5	20.5	5.5
EKF	22.5	0.5	22	1	23	3
Total ICI	18	5	18.5	5.5	19	7

Table 3.4: Required SNR and improvement for BER of 10^{-2} for BPSK

Method	ε =0.05	Gain(dB)	ε =0.15	Gain(dB)	ε =0.30	Gain(dB)
STD OFDM	20		23		26	
SC	20	0	18	1	20.5	13
EKF	17	3	22	6	23	20.5
Total ICI	20	0	18.5	20	19	20

Table 3.5: Required SNR and improvement for BER of 10^{-2} for 4-QAM

CHAPTER 4

CONCLUSION

4.1 Conclusion

In this project, three methods were explored for mitigation of the ICI. The ICI self-cancellation (SC) and the extended Kalman filtering (EKF) method and Total ICI cancellation schemes are proposed. The choice of which method to employ depends on the specific application. For example, self cancellation does not require very complex hardware or software for implementation. For small alphabet sizes (BPSK) and for low frequency offset values, The SC scheme delivers good performance in terms of BER. However, for higher order modulation schemes, the EKF and perform better. The self-cancellation technique does not completely cancel the ICI from adjacent sub-carriers. However, it is not bandwidth efficient as there is a redundancy of 2 for each carrier.

On the other hand, the EKF method does not reduce bandwidth efficiency as the frequency offset can be estimated from the preamble of the data sequence in each OFDM frame. However, it is more complex implementation method compared to SC method. In addition, this method requires a training sequence to be sent before the data symbols for estimation of the frequency offset. It can be adopted for the receiver design for IEEE 802.11a because this standard specifies preambles for every OFDM frame. The preambles are used as the training sequence in estimating the frequency offset.

The Total ICI cancellation Takes advantage of the orthogonality of the ICI coefficient matrix and it can eliminate the ICI experienced OFDM systems almost completely and provide significant BER improvement which almost matches the BER performance of OFDM system without ICI at all. The Total ICI Cancellation scheme not only provides better performance, it doesn't reduce the bandwidth efficiency of OFDM system like many existing ICI cancellation methods do. The Total ICI Cancellation scheme achieves such superb performance at a very reasonable computational complexity which linearly grows with the number of normalized frequency offset quantization

4.2 Scope of Future Work

Following are the areas of future study which can be considered for further research work.

1. This self cancellation technique and Extended Kalman filter method can also be applied under different channel conditions such as Rayleigh fading channel, urban area channel, rural area channel etc.

2. The sequential Monte Carlo (SMC) method called sequential importance sampling (SIS) can be implemented which requires very lower computational complexity and estimates channel by using frequency offset values.

References

[1]. Saltzberg, B."Performance of an efficient parallel data transmission system. "*Communication Technology, IEEE Transactions on* 15.6 (1967): 805-811.

[2]. Chang, R. W., and R. Gibby. "A theoretical study of performance of an orthogonal multiplexing data transmission scheme." *Communication Technology, IEEE Transactions on* 16.4 (1968): 529-540.

[3]. Salz, J., and S. B. Weinstein. "Fourier transforms communication system."*Proceedings of the first ACM symposium on Problems in the optimization of data communications systems*. ACM, 1969.

[4]. Weinstein, S., and Paul Ebert. "Data transmission by frequency-division multiplexing using the discrete Fourier transforms." *Communication Technology, IEEE Transactions on* 19.5 (1971): 628-634.

[5]. Barnett, W. "Multipath fading effects on digital radio." *Communications, IEEE Transactions on* 27.12 (1979): 1842-1848.

[6]. Cimini Jr, Leonard. "Analysis and simulation of a digital mobile channel using orthogonal frequency division multiplexing." *Communications, IEEE Transactions on* 33.7 (1985): 665-675.

[7]. Ahn, J., and H. S. Lee. "Frequency domain equalization of OFDM signals over frequency nonselective Rayleigh fading channels." *Electronics letters* 29.16 (1993): 1476-1477.

[8]. Moose, Paul H. "A technique for orthogonal frequency division multiplexing frequency offset correction." *Communications, IEEE Transactions on* 42.10 (1994): 2908-2914.

[9]. Zhao, Yuping, and S-G. Haggman. "Sensitivity to Doppler shift and carrier frequency errors in OFDM systems-the consequences and solutions."*Vehicular Technology Conference, 1996.'Mobile Technology for the Human Race'. IEEE 46th*. Vol. 3. IEEE, 1996.

[10]. Muschallik, Claus. "Improving an OFDM reception using an adaptive Nyquist windowing." *Consumer Electronics, IEEE Transactions on* 42.3 (1996): 259-269.

[11]. Armstrong, Jean. "Analysis of new and existing methods of reducing intercarrier interference due to carrier frequency offset in OFDM." *Communications, IEEE Transactions on* 47.3 (1999): 365-369.

[12]. Nee, Richard van, and Ramjee Prasad. *OFDM for wireless multimedia communications*. Artech House, Inc., 2000.

[13]. Zhao, Yuping, and S-G. Haggman. "Intercarrier interference self-cancellation scheme for OFDM mobile communication systems." *Communications, IEEE Transactions on* 49.7 (2001): 1185-1191.

[14]. Coulson, Alan J. "Maximum likelihood synchronization for OFDM using a pilot symbol: analysis." *Selected Areas in Communications, IEEE Journal on* 19.12 (2001): 2495-2503.

[15]. Proakis, John G. "Digital Communications (ISE)." (2001).

[16]. Harada, Hiroshi, and Ramjee Prasad. *Simulation and Software Radio for Mobile Communications (Book)*. Artech House on Demand, 2002.

[17]. Rappaport, Theodore S., et al. "Wireless communications: Past events and a future perspective." *IEEE Communications Magazine* 40.5 (2002): 148-161.

[18]. Erwa, Elmustafa, et al. "INTER-CARRIER INTERFERENCE CANCELLATION FOR OFDM SYSTEMS." (2003).

[19]. Yang, Feng, Kwok H. Li, and Kah C. Teh. "A carrier frequency offset estimator with minimum output variance for OFDM systems." *Communications Letters, IEEE* 8.11 (2004): 677-679.

[20]. Bahai, Ahmad RS, Burton R. Saltzberg, and Mustafa Ergen. *Multi-carrier digital communications: theory and applications of OFDM*. Springer Verlag, 2004.

[21]. Seyedi, Alireza, and Gary J. Saulnier. "General ICI self-cancellation scheme for OFDM systems." *Vehicular Technology, IEEE Transactions on* 54.1 (2005): 198-210.

[22]. Amasa, Ravitej. *Inter Carrier Interference Cancellation in OFDM Systems*. Diss. 2009.

[23]. Li, Xue, et al. "Total inter carrier interference cancellation for OFDM mobile communication systems." *Consumer Communications and Networking Conference (CCNC), 2010 7th IEEE*. IEEE, 2010.